Quick Acoustic Analysis

of

Volley 5, 3rd Burst

Front Row – Center Stage

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https://github.com/Vegas-Oct-1-Sounds/Gunshot-Acoustics

Ver. 1.01
09/14/19

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Introduction

By way of example, this paper is an introduction to some of the tools and techniques which can be applied in assisting audio analysis of gunshot sounds recorded October 1, 2017.

- audio waveform analysis
- analysis of power (energy) distribution
- frequency decomposition of muzzle waves and shock waves
- spectral contrast analysis
- muzzle & shock wave duration, timing, velocity, acceleration, r.p.m.
- time of arrival differences ("lag") between shock wave(s) and muzzle blast(s)
- "lag" as a function of longitude and latitude

Background

Numerous sources explain the theory and application of gunshot acoustics (1–17),(1) Leading expert in the field, Robert C. Mayer Ph.D., P.E., publications are available at:

Publications: http://www.montana.edu/rmaher/publications
Resume: http://www.montana.edu/rmaher/documents/Maher_CV.pdf .

The possible sounds generated by gunfire are:

- muzzle blast wave
- one to four shock wave(s) from supersonic projectile(s)
- reflections (ground or otherwise) from muzzle
- reflections (ground or otherwise) from shock waves
- projectile impact sounds
- ricochet sounds
- "whistling" from sub-sonic projectiles
- shell casings hitting a surface
- noises from weapon mechanics

Muzzle waves and shock waves are the main focus of this paper.

Tools

All waveforms and spectrograms were created with https://sonicvisualiser.org. Graphs were created using the matplotlib library in Python. Numpy and SciPy python libraries for numerical analysis. LibreOffice for presentation and worksheets.

Video Source

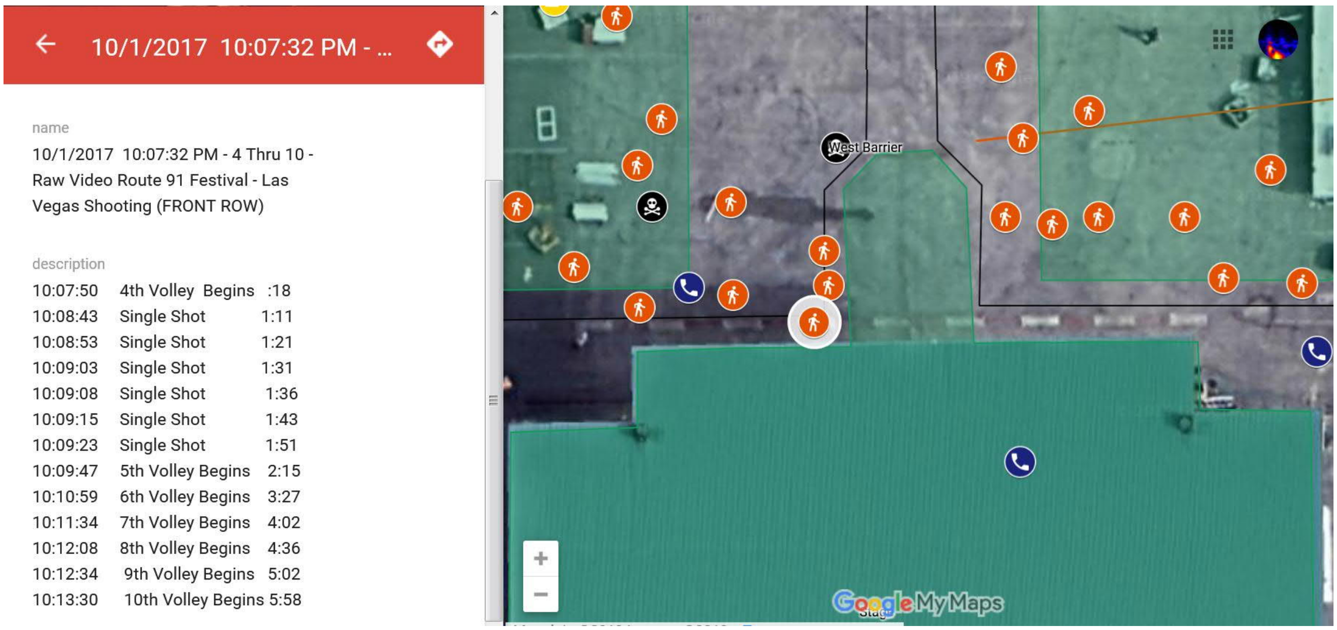

Figure 1: Source Location

The above image was taken from the Vegas Shooting Map project located at: http://vegasshootingmap.com The video was filmed as the highlighted red dot. The location is very near the front row of the stage in the middle adjacent to some lattice.

The full video is located at:

https://youtu.be/l-IEme0aGMA

From this full video a 1.37 second segment beginning at 2:23.05 is considered.

This segment contains a sequence of sounds which compose the 3rd burst of volley five, occurring approximately at 10:09:55 PM.

Listen

Regions of interest are determined by listening. There can be heard about twelve distinct “sounds”. The first sounds are like a “snap” or “crack” while the later ones are more similar to a “boom” or “thud”. In the middle of those two groups are sounds with a bit more robustness. Screaming and a siren can also be heard in the background.

The gunshot sounds are very audible over the background noise. Both the “crack” and “thud” sounds are quite “loud”, with perhaps the “crack” a little more, particularly near the middle of the clip. The first few shots are not as “regular” in cadence as the final four shots. The first few shots are composed of higher frequencies than the last four. The siren sounds distant, the screams sound closer than the siren.

Waveform (plot of signal amplitude v. time)

After listening to the extracted audio segment, several graphical plots are constructed. The first is a waveform plot consisting of signal amplitude plotted against time.

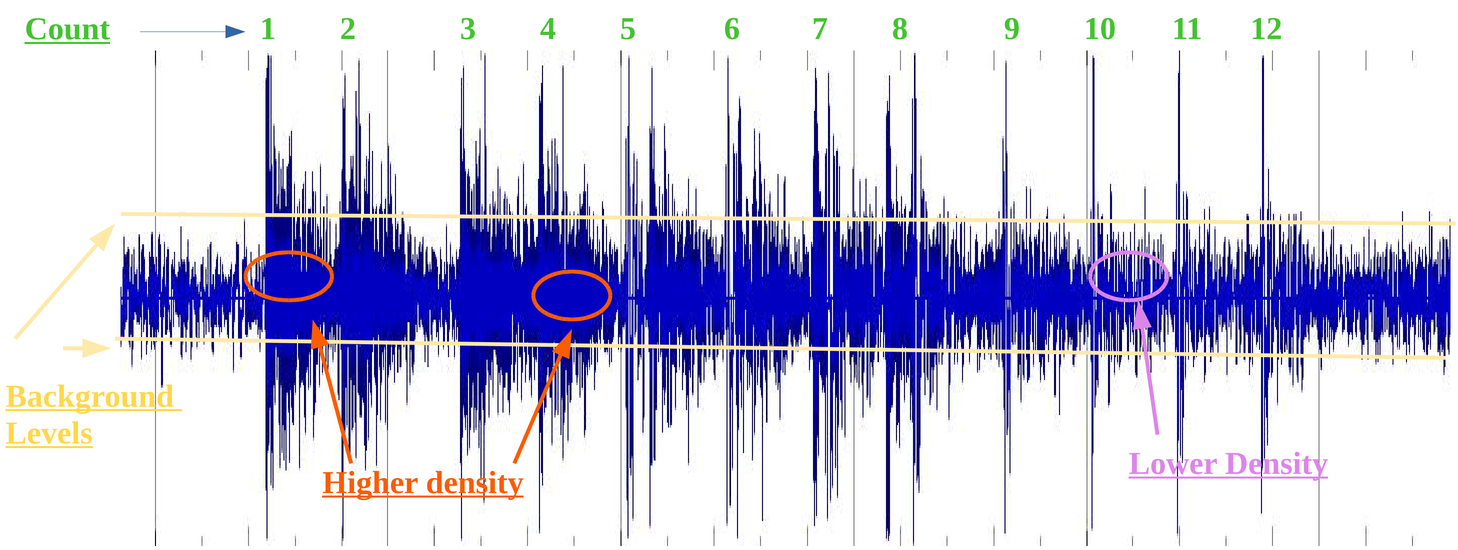

Figure 2: Signal Amplitude v. Time

Observations:

- at least 12 distinct percussive (pulses) sounds.
- sounds at start are “higher” density, more noisy, higher frequency and less regular in cadence
- sounds near end are “lower” density, lower frequency and more regular in cadence
- possible overlap between high and low density signals
- decent signal to noise ratio (amplitude larger than background)
- onsets (starts) sharp and clear

Spectrogram – Db^2 (a measure of energy)

From a waveform plot we graduate to spectrograms for more detailed analysis. Spectrograms come in many flavors, the first shown below is a plot of energy distribution in the form of frequency versus time plot where energy density is displayed as ever increasing brightness of color. Both frequency and time are plotted on linear scales.

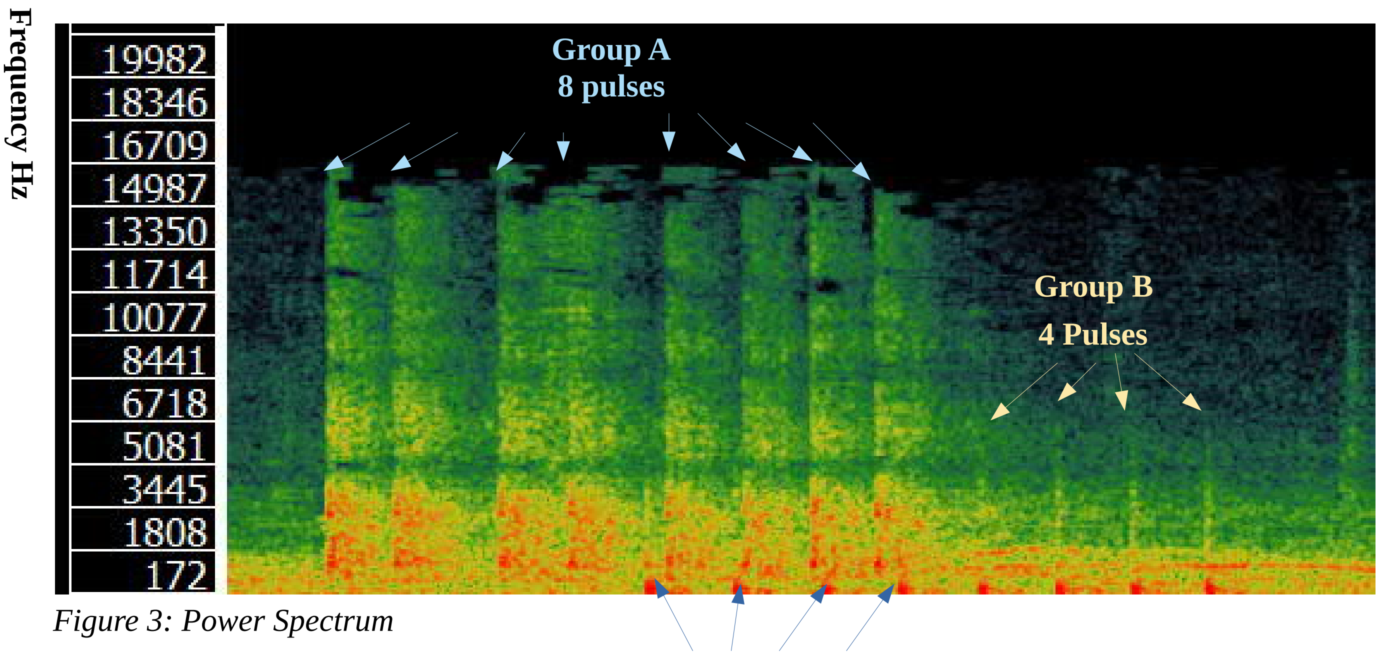

Figure 3: Power Spectrum

Observations:
- at least 12 distinct percussive sounds
- two unique frequency groups (group A and group B)
- Group A (first 8 pulses) are broadband and have their energy spread over a large range of frequencies.
- Group A spread (smeared/fuzzy) over time.
- Group B (last 4 pulses) much narrower frequency band (shorter up and down)
- Group B sharper in time (narrower pulse)
- close examination (large magnification) suggest 4 more pules buried within the first 8 that are similar to last 4 bringing total to possible 16 total pulses.

Spectrogram – Log Frequency v Time

While a power spectrum like Db[2] is good at revealing major events, the linear scale used for frequency masks many of the details. Changing the frequency scale to logarithmic permits closer examination of the lower frequencies. Also changed is the color scale for easy identification, green spectrograms are power, blue coloring is frequency with logarithmic scale. Most muzzle sounds, talking, sirens, and other sounds are easier to examine with the logarithmic scale than a linear scale as the majority of sounds occur below 2,500 Hz.

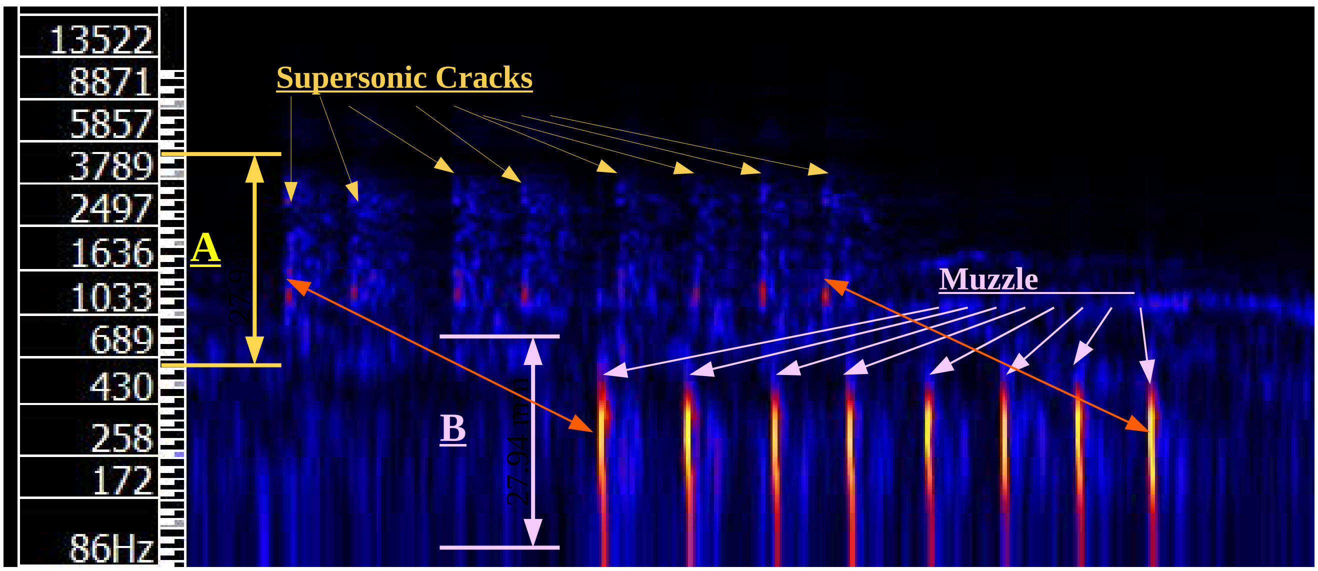

Figure 4: Log Frequency v. Time

Observations

- Supersonic “Cracks” – shock wavefront – frequency region (A)
  - 8 pulses in frequency region A (upper frequencies)
  - frequency region A consistent with theory predicted frequencies
  - (A) centered between 3,789-450 Hz
  - wave/sound smeared over time producing fuzzy delineation
  - possible indirect path of propagation
  - irregular timing between rounds
- Muzzle blast wavefront – frequency region (B)
  - 8 pulses in frequency region B (lower frequencies)
  - frequency region B consistent with theory predicted frequencies
  - (B) centered between 689-86 Hz.
  - Fairly regular timing between rounds, near 0.nnn secs
- some overlap in frequencies between two groups

- “red” lines indicate “lag” between arrival of supersonic shock wave and arrival of muzzle wave wave.
- For “Cracks” 5,6,7,8, the arrival of muzzle events 1,2,3,4 occur close to each accordingly and will be heard as 4 single events due to the limitations of the hearing process, but which can be distinguished separately at slower playback speeds. Each of these 4 events will have a “richer” / “fuller” sound than either the “Crack” alone or the muzzle alone. This phenomena leads to a total of 12 sounds “heard” while listening to the recorded audio.
- In listening, the “volume” of the cracks seems to be about the same as the booms, with the difference given to the cracks.

Spectral Contrast Color Plot

A color spectral contrast plot reveals how “sharp”, distinct and clear a sound is over its surrounding neighbors.

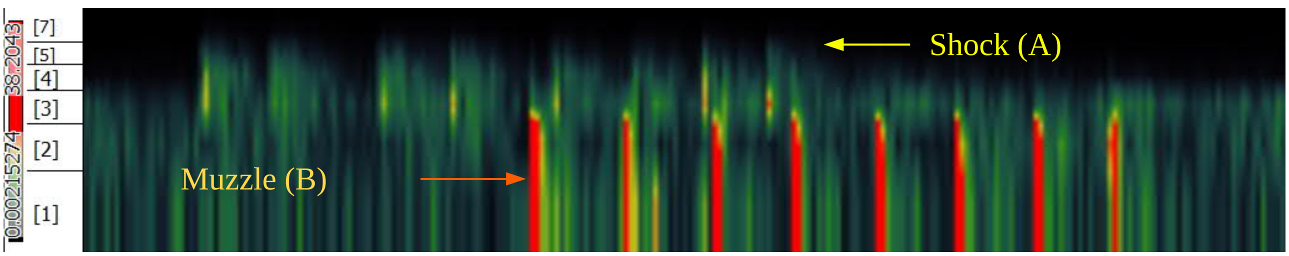

Figure 5: Spectral Contrast v Time

Observations:

- spectral contrast confirms and preserves regions A and B from log frequency plot.
- Region A – Shock waves
  - 8 weaker pulses in bands 3 and 4.
  - contrast with background noise weak, most likely due to “smearing” of energy
  - still 8 pulses, but of varying contrast, may indicate substantial trajectory deviations for rounds 2,3, and 6

- Region B – Muzzle waves
  - 8 strong pulses in the band 1 and 2
  - some indication of reflections with weaker offset bans of lower intensity

Muzzle Wave Data

An “instants” layer in Sonic Visualizer was overlayed with the frequency plot and the onset of each sound marked. The video times below are taken directly from that instants layer with no modification. In marking the locations of each pulse, care was taken to minimize the error to 2 milliseconds.

Table 1: Muzzle Waves Timing & Properties

Shot No.	Vid. Time	Delta	Delta Delta	R.P.M.
1	143.505215420			
2	143.612698413	0.1075		558.23
3	143.719954649	0.1073	-0.000227	559.41
4	143.812925170	0.0930	-0.014285	645.37
5	143.909297052	0.0964	0.003401	622.59
6	144.004535147	0.0952	-0.001134	630.00
7	144.095011338	0.0905	-0.004762	663.16
8	144.186621315	0.0916	0.001134	654.95
Avg.		**0.0973**		**619.10**

“**Vid. Time**” is the location of the sound within the video, measured in seconds and relative to the start of the video. From these relative times, differences between each pulse of sound was calculated and entered in to the **Delta** column. Delta is the time between shots. The time between Delta’s is calculated and entered into the **Delta Delta** column. The **R.P.M**. column is the estimated rounds per minute or cyclic rate of fire calculated from the Delta.

r.p.m. = (1/Delta)*60.

Total duration of muzzle events: 0.680 seconds.
The average time between shots was 97.3 milliseconds.
The average r.p.m. for these shots was 619.

Shock Wave Data

An “instants” layer in Sonic Visualizer was overlayed with the frequency plot and the onset of each *shock wave sound* marked. The video times below are taken directly from that instants layer with no modification. In marking the locations of each pulse, care was taken to minimize the error to 2 milliseconds.

Table 2: Supersonic Shock Wave(s) Timing & Properties

Shot	**Time Since Start**	**Delta**	**Delta Delta**
1	143.117188209		
2	143.199274376	0.0821	
3	143.326666667	0.1274	0.0453
4	143.411020408	0.0844	-0.0430
5	143.529591837	0.1186	0.0342
6	143.622675737	0.0931	-0.0255
7	143.705668934	0.0830	-0.0101
8	143.783582766	0.0779	-0.0051
Avg.		**0.0952**	

The content of each column is as described in muzzle blast table but applied to the supersonic shock wave sounds.

Total duration of shock events: 0.662
Average time between shock wave events 95.2 milliseconds

Lag Calculations

The shock wave is the first to arrive on the scene followed sometime later by it's corresponding muzzle wave. The time between these two events, commonly referred to as "lag" is an important measure in gunshot acoustics.

Using Sonic Visualiser the time between each shock wave and it's corresponding muzzle wave was measured directly and entered into the "lag" column. Referring to Figure 4, the red double headed arrows illustrates where lag times were measured for the first and last shots.

Table 3: Lags & Properties

Shot	Lag	Delta
1	0.388	
2	0.411	0.0230
3	0.394	-0.0170
4	0.400	0.0060
5	0.377	-0.0230
6	0.378	0.0010
7	0.389	0.0110
8	0.400	0.0110
Avg.	**0.392**	**0.0131**

Max lag: 0.411
Min lag: 0.377
Difference: 0.034

These measurements indicate that on average, the person "heard" the supersonic "cracks" 0.392 seconds before they heard the corresponding muzzle retort. Not a large difference, but certainly detectable by the human hearing system. Note that several rounds could be fired in this length of time. This is illustrated in Figure 4 where four sonic cracks are recorded before the first muzzle wave is recorded. Put another way four bullets have "traveled by" before the first muzzle blast is heard. On the opposite end of the burst, four muzzle blasts are recorded after the last shock wave is recorded.

Several factors determine "lag":

- bullet speed
- bullet trajectory
- speed of sound

- shooters location
- recording location
- wind

Since “lag” varied from one shot to the next, some combination of changes to these factors should be responsible.

Multiple Lag Measurements

By way of comparison, a few lags from several sources, and a sampling of volleys were measured and plotted against longitude and latitude in Figure 6. A relatively decent and qualitative measure of the expected “lag” for any recording location. This segment of video lies within a yellow region suggesting that the “lag” should be between 0.32 to 0.40 seconds. A reasonable match to the measured average of 0.392.

Given this close match and given that the recording location was static, it’s easy to assert that the major changes in “lag” for this burst were a function of the bullet trajectory (change in distance between bullet and recording location). Changes to initial bullet speed, wind, temperature etc. are considerations, but most likely account for a few percentage points in the “lag” variations.

In reviewing Figure 6, it’s apparent that there is a symmetry. This symmetry exists because “lag” is symmetrical about the path of the bullet. It is also known that “lag” is smaller near the shooting location. Using these two bits of information a line drawn NE to SW fits the bill and identifies the shooters longitude and latitude (not elevation) as somewhere along the line where the measured lag is smallest. The plot also converges for all measured volleys to a relatively small region near the Mandalay Bay. Based on the “roundness” of the low value lag regions, the graph also indicates that the shooting location was elevated.

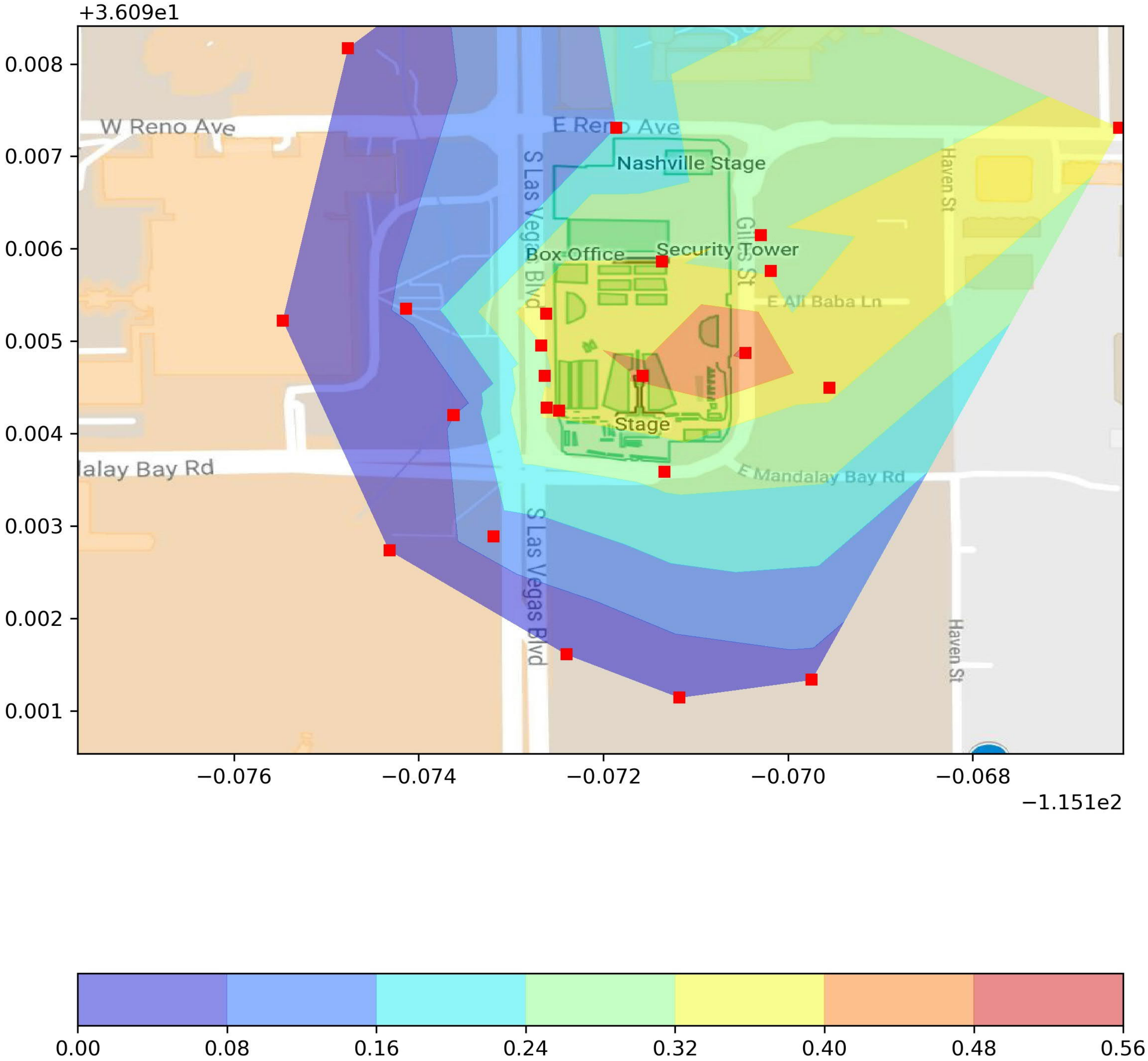

Figure 6: Multiple Lag Measurements, Lag v Longitude/Latitude

General Questions & Observations

1. How do we know these are gunshots?

   The same way we recognize a car, from past experiences. That is, numerous well researched and well documented actual gunshots are available. These gunshots are subject to the same analysis done here and provide good matches (a matter for another paper). As well as comparing this set of sounds to known gunshots, this analysis provides characteristics (frequency, duration, power distribution, spectral contrast, waveform, timing) that match acoustic gunshot theory. There are also documented cases of gunshot impact/wounds/deaths in the vicinity of the recorded sounds.

2. How do we know these sounds aren't speaker/lrad/magic device generated?

   The strongest argument against an artificial sound source is the variation in "lag" from location to location. That is, if you look at Figure 6, the reader can see that lag varies by location. If a single source of sound imitated a sonic wave followed by a muzzle blast with 0.2 seconds between, then that difference would be recorded as 0.2 seconds for all recording locations. Since it is not, then a single imitation sound source is not the culprit. And if someone want's to argue multiple sound sources, then they had better come up with enough sources to cover hundreds of recordings each with a different lag.

3. The cadence (time between rounds) of the supersonic shock waves is different from the cadence of the muzzle waves. This is quite often the case. Muzzle sound propagation primarily depends on the speed of sound and the distance between the shooter and the recorder (two variables) and if both the shooter and recorder are fixed in location, then the relative time of arrival will remain the same. Shock waves on the other hand are continually generated by the supersonic projectile and the time of arrival for them is primarily dependent on speed of sound, speed of projectile, downrange distance and cross-range "miss" distance (four variables). Thus even if both shooter and recorder remain at the same location between rounds, the shock wave may arrive at different times due to variations is either the bullet speed or bullet trajectory which alters the downrange and/or cross-range distance and/or timing.

4. Count of events in group A matches the count of events in group B. As expected for audio which records both muzzle and shock wave.

5. Lag varies from shot to shot. As would be expected when the bullet does not travel the exact same trajectory/path each round.

6. Frequency range of group A from frequency plot agrees well with theory for supersonic projectile shock wave.

7. Frequency range of group B from frequency plot agrees well with theory for muzzle blast waves.
8. Good frequency separation between groups A and B (shock v muzzle)
9. Supersonic shock wavefront precedes muzzle blast waves as predicted by theory.
10. Existence of supersonic shock wave implies rifle.
11. Existence of relatively large lag implies both substantial distance downrange and relatively small cross-range “miss” distance.
12. Timing of muzzle sounds ambiguous, could be automatic weapon or could be bump-stock. That is, this volley has very regular almost mechanical times between rounds. However this b rst should be considered in the general context of all bursts within volley 5 which are less r gular in timing. See https://github.com/Vegas-Oct-1-Sounds/Gunshot-Acoustics/blob/master/Papers/Variance.pdf Vegas Cyclic Rate & Variance for a more detailed background and why this volley was not produced by a 240 series (belt or magazine fed) machine gun.
13. “lag” consistent with multiple lags measured from multiple videos with multiple volleys all indicating an elevated shooting location in a south westerly direction from the venue.

Summary

To the ear, this segment presents twelve “shots”, closer examination demonstrates that there are only eight shots each producing two sounds, one from the supersonic projectile, and another from the exploding gases exiting the muzzle of the weapon. The supersonic shock wave arrives first, followed some time later by the muzzle sound. In this instance all of these phenomena are quantifiable with the aid of Fourier transforms available via Sonic Visualiser.

Thus a total of sixteen sounds are generated by eight rounds of fire. For this location the time of arrival of the shock wave and the time of arrival of the muzzle wave differ by about **0.392** seconds, which causes the first muzzle sound to arrive at approximately the same time as the fifth shock wave and overlap the next three shock waves (a total of four overlapping). Overall this overlapping extends the apparent length of the burst.

While the ear is good at detection, it is often poor and sometimes misleading about the character of gunshot sounds as demonstrated with this example.

From all this analysis what can be surmised about the weapon, ammunition, shooter, and location of gunfire?

First and foremost this analysis provides real measurements founded on real tools, with a sound basis in known and vetted theory of gunshot acoustics. The tools are available to anyone, the measurements are reproduce able, and the theory behind the analysis is readily available on the net.

Given that a supersonic shock wave is recorded, then the weapon is likely a rifle. Given the rapid rate of fire and low variance of timing between rounds, it's likely a machine gun or some sort of trigger mechanism was used. Based on research presented elsewhere, the probability of machine gun use is lower than bump-fire use.

Smooth evenly spaced muzzle wave arrivals suggest that the distance between the shooter and recorder was fixed. That is, neither was moving significantly.

The relatively large "lag" suggests a distant shooter and relatively close proximity to the bullet path. "lag" variance suggest poor control of muzzle positioning and/or large variations in projectile speed. If ammunition is eliminated as a source of variation in "lag" then very poor control of muzzle positioning is indicated (for example no tripod).

The "smearing" of the shock waves indicates multiple sources of reflections very nearby and/or an indirect path of arrival. Given the relatively large power spectrum, the smear was likely related to local sources of reflection.

Much more information can be coaxed out of this audio sample, but is beyond this simple presentation.

When multiple "lags" are combined and plotted against longitude and latitude as in Figure 6, a clear picture emerges, and this volley from this audio is consistent with that picture; a shooter located in an elevated position in a south west direction from the venue whose shooting location was fixed.

Appendix – A – Wisdom from Gunshot Acoustic Theory

- “The bow wave only propagates forward of the line-of-fire and within the mach angle defined by the bullet's speed.”(18)
- “The noise generated at a small-arms range has two components: the muzzle blast and the sonic boom, bow wave noise generated by the flight of the bullet.”
- “The muzzle blast is caused by the powder charge exploding in the gun chamber and can be modeled as an explosion of some equivalent weight of TNT with some directivity specific to the weapon being fired. Therefore, except for the nonuniform directivity pattern, which will be discussed later, the muzzle blast can be modeled by a simple point source located at the point of fire. This leads to the conclusion that the muzzle blast should propagate in a spherical pattern. ”
- Considering that the energy decays in proportion to the surface area of a sphere, it can be shown that the SEL decays, purely due to geometric spreading, as R**2, where R is the distance from the point of fire to the point of interest. This is equivalent to -6 decibel (dB) per doubling of distance.”
- The bow wave portion of the shot noise is caused by the bullet traveling faster than the speed of sound. As long as the bullet's mach number exceeds 1, a bow wave will be continually produced along the bullet's trajectory.
- The amplitude of this bow wave depends on the geometry and caliber of the bullet, while the direction of propagation relative to the trajectory is determined by the speed of the projectile.
- As shown in Figure 1, a supersonic bullet causes a bow wave with a mach angle alpha (oa). The bow wave propagates perpendicular to the mach angle, creating a conical spreading pattern (Figure 2). It has been shown that the SEL of the bow wave portion of the gunshot depends on the surface area of this conical shape (Thompson). The SEL decays nonlinearly in the near field, where the pressure is very large. This nonlinear model (Pierce 1989) suggests that the SEL decays in direct proportion to h-3'4, where h is the horizontal distance from the bullet trajectory to the point of interest. The distaince the bow wave has traveled perpendicular to the mach angle is related to h by r=h cos (a) [Eq 21 Consequently, r is directly proportional to h and the SEL decays in the near field in direct proportion to r**(3/4). This can be stated as -4.5 dB per doubling of distance r. In the far field, and for smaller peak pressures, the SEL decay can be modeled by a linear model that depends solely on the geometrical spread-ing effects of the conical surface. When this is the case, the SEL decays in proportion to r'', which is equivalent to -3 dB per doubling of distance.
- The one-third octave analysis of the gun shots showed that the bow wave is centered around the 4 kHz band. The muzzle blast contains much lower frequency energy, with the flat weighted

data centered around 200 Hz and the A-weighted data centered around 250 Hz. Because of the large difference in the main components of spectral energy between the bow wave and the muzzle blast, A-weighting the signal has a very large effect. An A-weighting filter attenuates the muzzle blast fundamental frequency by about 13 dB while it increases the bow wave by about 1 dB. Thus the A-weighting significantly affects comparison of the bow wave and muzzle blast. Both flat and A-weighted data are presented as appropriate; however, only A-weighted data are used for comparison.

- This research showed the spectral data gathered from the small arms fire and identified the bow wave and muzzle blast as the important components. The decay rates of the different components, as observed along the microphone array, were also shown. Considering the geometry of the test setup, the bow wave is the dominant component at all test locations. Along lines that interest the line of fire at angles greater or lesser than the one specifically tested in this research, the bow wave will not be at a maximum. Therefore, along these lines the muzzle blast predominates a distances less than 10,000 m. For example, directly in front of the gun the muzzle blast has a directivity factor of 0 dB and it will predominate within a few hundred meters. The muzzle blast will always predominate in areas along lines that interest the line of fire at angles greater than 90 minus the mach angle (ac). But the bow wave must be considered if communities are within 10,000 m (10 kin) of the firing range and lie along lines that interest the line of fire at an angle less than 90-a.

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